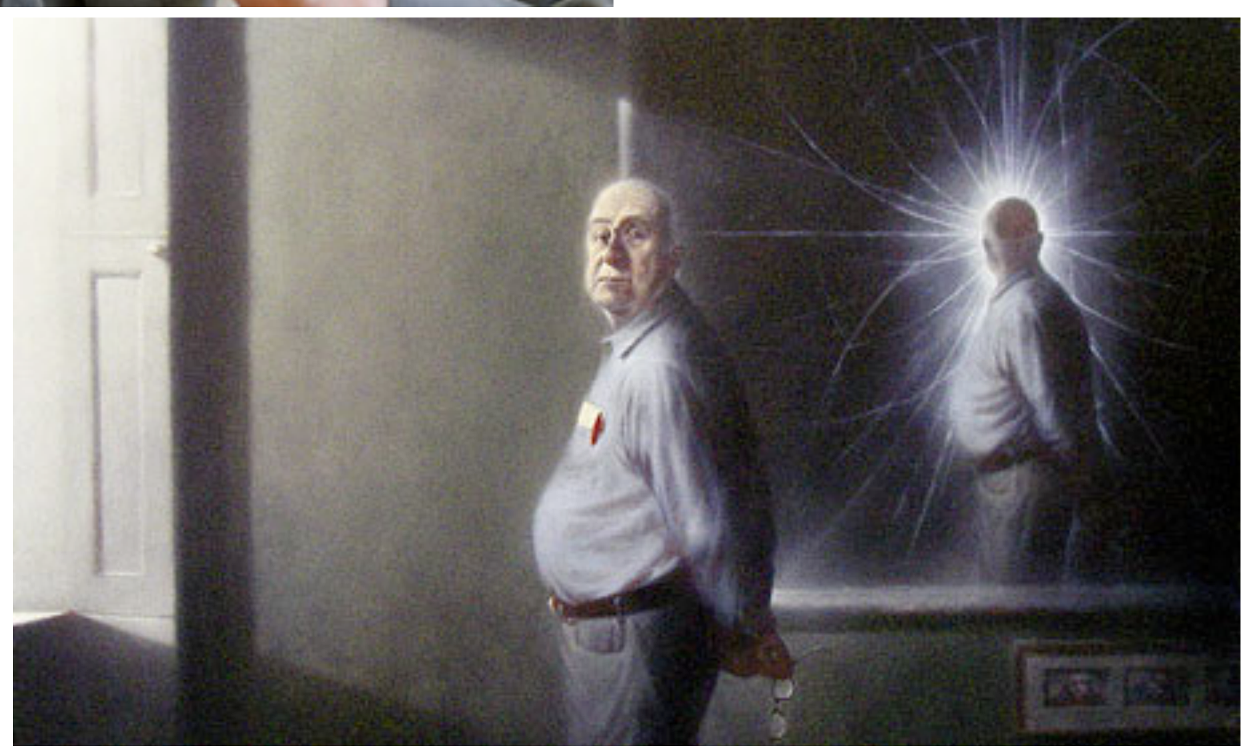
Particle Physics

Dr Victoria Martin, Spring Semester 2013

Lecture 18: Higgs

- ★Review of electroweak theory
- ★Spontaneous Symmetry Breaking
- ★W and Z bosons
- ★The Higgs mechanism and the Higgs boson



Weak Isospin and Hypercharge

- QED couples to electric charge; QCD couples to colour charge...
- Electroweak force couples to two "charges".
  - **Weak Isospin:** total and third component T, T_3. Depends on **chirality**
  - **Weak Hypercharge,** Y In terms of electric charge Q: $Y = 2\,(Q - T_3)$
    - All right-handed fermions have $T=0$, $T_3=0$
    - All left-handed fermions have $T=½$, $T_3=±½$
    - All left-handed antifermions have $T=0$, $T_3=0$
    - All right-handed antifermions have $T=½$, $T_3(\bar{f})=-T_3(f)$

Lepton	T	T_3	Y	Quark	T	T_3	Y
$\nu_{eL}, \nu_{\mu L}, \nu_{\tau L}$	½	+½	-1	u_L, c_L, t_L	½	+½	⅓
e_L, μ_L, τ_L	½	−½	-1	d_L, s_L, b_L	½	− ½	⅓
ν_R	0	0	0	u_R, c_R, t_R	0	0	4/3
e_R, μ_R, τ_R	0	0	-2	d_R, s_R, b_R	0	0	−⅔

Summary of Electroweak Unification

- **Weak Isospin:** total and third component T, T_3. Depends on **chirality**
- **Weak Hypercharge,** Y In terms of electric charge Q: $Y = 2\,(Q - T_3)$
  - ➡ We introduced an SU(2) symmetry which has three boson W^1, W^2, W^3 coupling to weak isospin with a coupling constant g_W
  - ➡ We introduced a U(1) symmetry which has one boson B^0 coupling to weak hypercharge with a coupling constant g'_W
  - ➡ Bosons mix to give the physical W^+, W^-, Z and γ bosons

$$W^+ = \frac{1}{\sqrt{2}}(W^1 - iW^2) \qquad W^- = \frac{1}{\sqrt{2}}(W^1 + iW^2)$$

$$Z^0 = W^3 \cos\theta_W - B^0 \sin\theta_W \qquad \gamma = W^3 \sin\theta_W + B^0 \cos\theta_W$$

  - ➡ Consistent with electromagnetism if $e = g'_W \cos\theta_W = g_W \sin\theta_W$

$$\sin^2\theta_W = \frac{g'^2_W}{g^2_W + g'^2_W}$$

All of the properties of electroweak interactions described by:

- the intrinsic charges (isospin and hypercharge) of the fermions
- the SU(2) ⊗ U(1) symmetry
- g_W and g'_W: free parameters that need to be measured

The Higgs Mechanism: Introduction

- The Higgs Mechanism was proposed in 1964 separately by Higgs and Brout & Englert.
- It introduces an extra field, ϕ, which interacts with the electroweak currents. The potential of the field is:

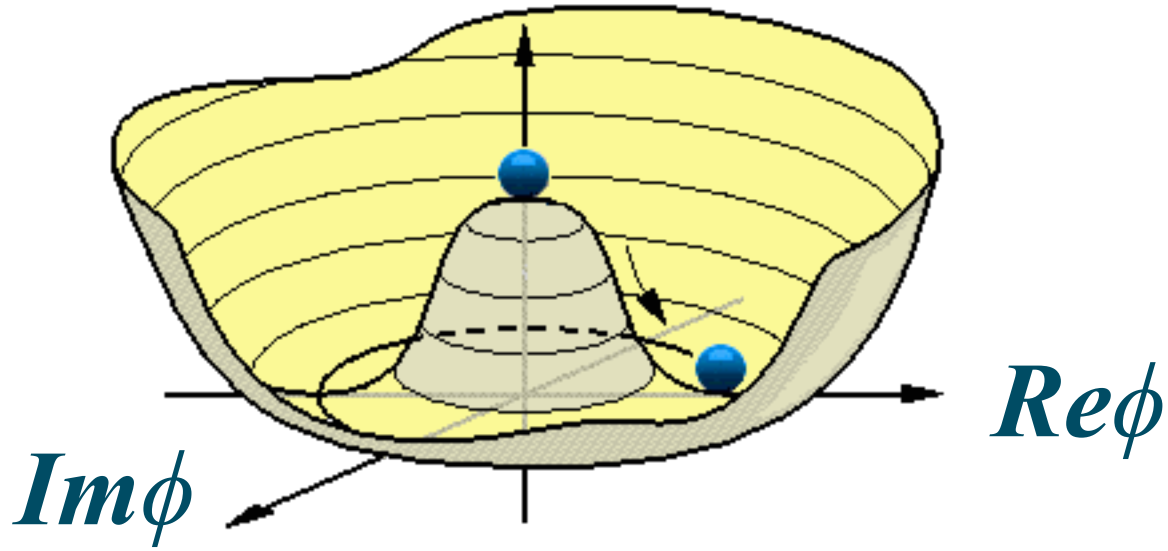
$$V(\phi) = -\mu^2 \phi^\dagger \phi + \lambda(\phi^\dagger \phi)^2 \quad \text{with } \mu^2 > 0, \lambda > 0$$

- The Higgs mechanism allows the ***W*** and ***Z*** bosons to have a mass. (Otherwise forbidden by the external symmetries.)

- Provides an explanation for fermion masses (***e***, $\boldsymbol{\mu}$, $\boldsymbol{\tau}$, **u**, **d**, **s**, **c**, **t**, **b**).

- P.W. Higgs pointed out that a further consequence would be the existence of a spin-0 boson: the Higgs boson, ***H***.

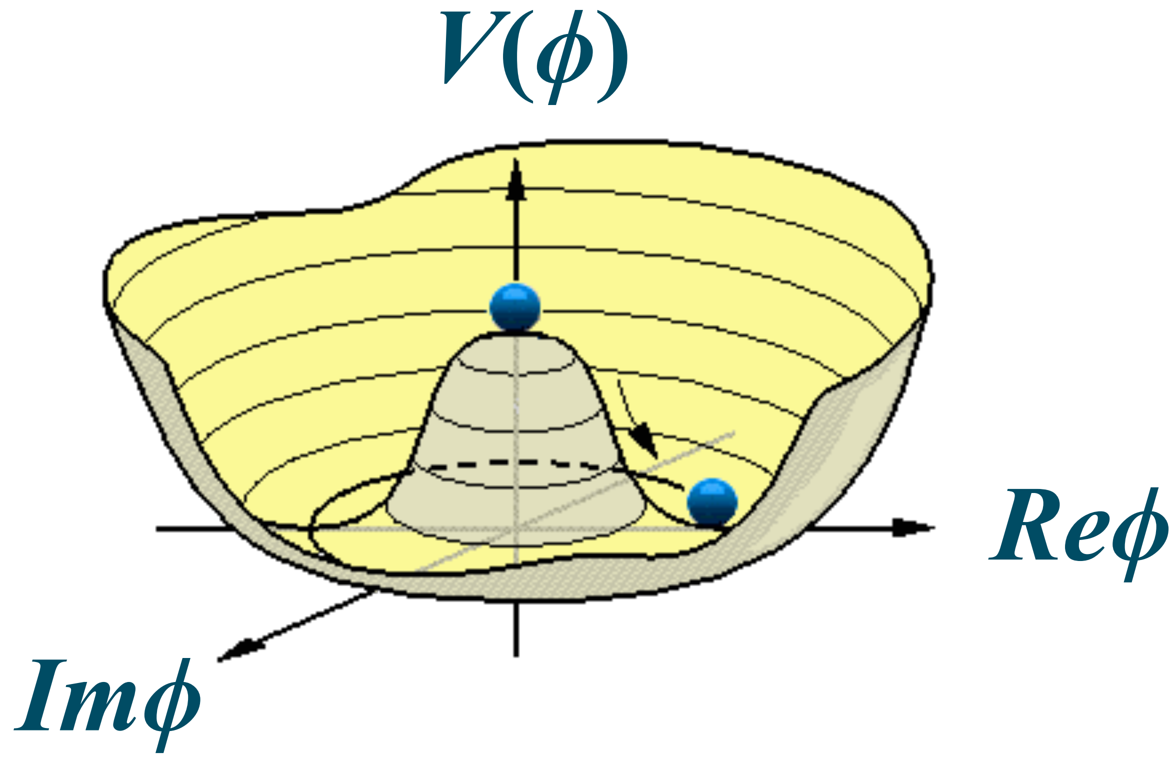
Spontaneous Symmetry Breaking



- Start with a system that has an intrinsic symmetry
  - ➡ Choosing a particular ground state configuration the symmetry is broken
  - ➡ If the choice is arbitrary, i.e. no external agent is responsible for the choice, then the symmetry is "spontaneously" broken
- Everyday example: A circle of people are sitting at a dining table with napkins between them. The first person who picks up a napkin, either with their left or right hand spontaneously breaks the L/R symmetry. All the others must do the same if everyone is to end up with a napkin.
- Physics example: In a domain inside a ferromagnet all the spins align in a particular direction. If the choice of direction is random, the underlying theory has a rotational symmetry which is spontaneously broken. The presence of an external magnetic explicitly breaks the symmetry and defines a preferred direction.

Higgs Potential

$$V(\phi) = -\mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2$$



- ϕ is complex function.

- $\mathbf{V(\phi)}$ is symmetric: the maximum symmetry occurs at ϕ**=0.**
- A circle of values minimise the potential at $\phi=\phi_0 \equiv -v/\sqrt{2}$ with $|\phi_0| = \dfrac{\mu}{\sqrt{2\lambda}}$
    - Any coordinate around the circle minimise the potential: $\arg(\phi_0)$ = **[0,2π)**
- The choice of which complex value of ϕ_0 is chosen spontaneously breaks the symmetry.
- The value of **v**, related to the value of $|\phi|$ at the minimum of the potential known as the vacuum expectation value. Measured to be **v = 246 GeV**

Standard Model Higgs Field

- In the Standard Model, the Higgs field is a complex isospin doublet:

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix} \qquad T = 1; \begin{array}{l} T_3 = +1 \\ T_3 = \ \ 0 \end{array}$$

ϕ^+ : +ve charged field
ϕ^0 : neutral field
ϕ_0 : minimum of field

- Higgs field has four degrees of freedom.

- In the Higgs mechanism (when the symmetry is spontaneously broken) three of these degrees of freedom are used to give mass to W^+, W^-, Z^0.
- This fixes three of the degrees of freedom: two charged and one neutral.

- The minimum of the potential ϕ_0 for ground state can then be written in terms of the remaining free parameter:

$$\phi_0 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$$

- Where v is related to the value of ϕ which minimises V: $v = \frac{\mu}{\sqrt{2\lambda}}$

Introducing the Higgs Boson

- Consider a fluctuation of the Higgs field about its minimum:

$$\phi(x) = \phi_0 + h(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}$$

- Substitute $\phi(x) = \frac{1}{\sqrt{2}}(v + h(x))$ into ***V(ϕ)*** and expand to second order in ***h(x):***

$$V(\phi) = -\mu^2 \left(\frac{v + h(x)}{\sqrt{2}}\right)^2 + \lambda \left(\frac{v + h(x)}{\sqrt{2}}\right)^4 = \ldots = V(\phi_0) + \underbrace{\lambda v^2}_{= \frac{1}{2} m_H^2} h^2 + \mathcal{O}(h(x)^3)$$

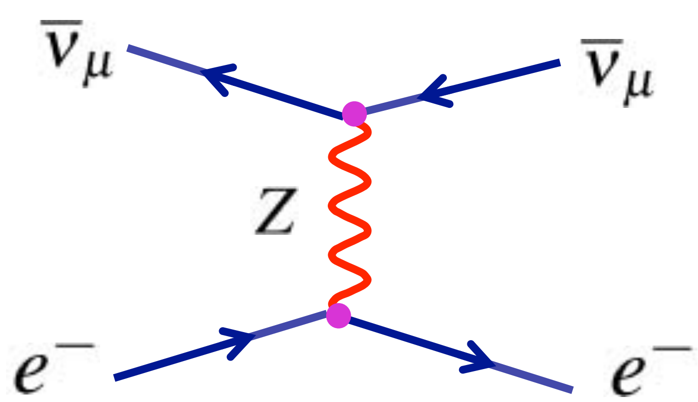
- In quantum field theory a term quadratic in the field describes a particle's mass.
- This fluctuation around the minimum of the potential describes a spin-0 particle with a mass $m = \sqrt{2\lambda} v$

- **The Higgs boson!**

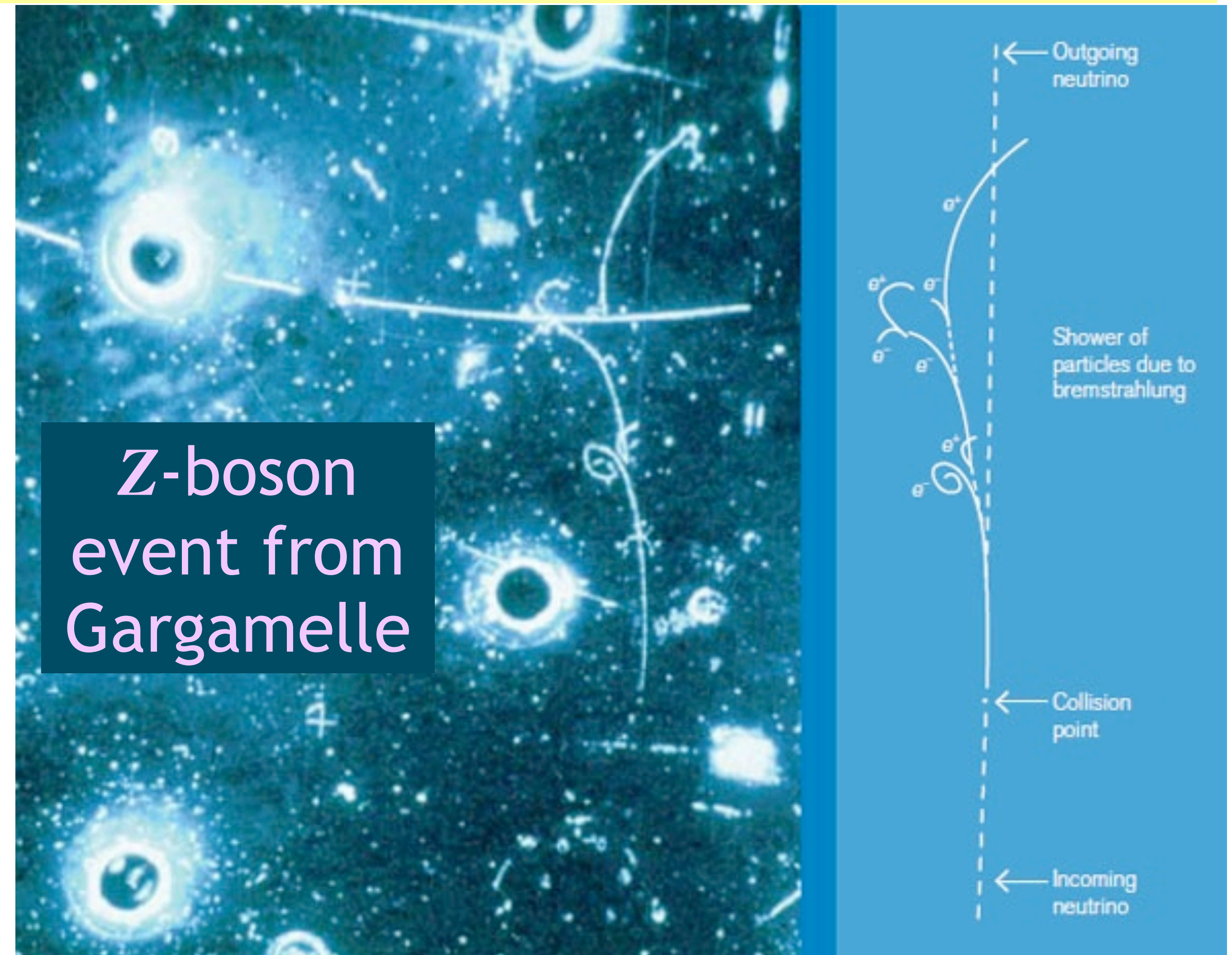
W and *Z* bosons

- *W*-boson interactions already been observed in beta decay

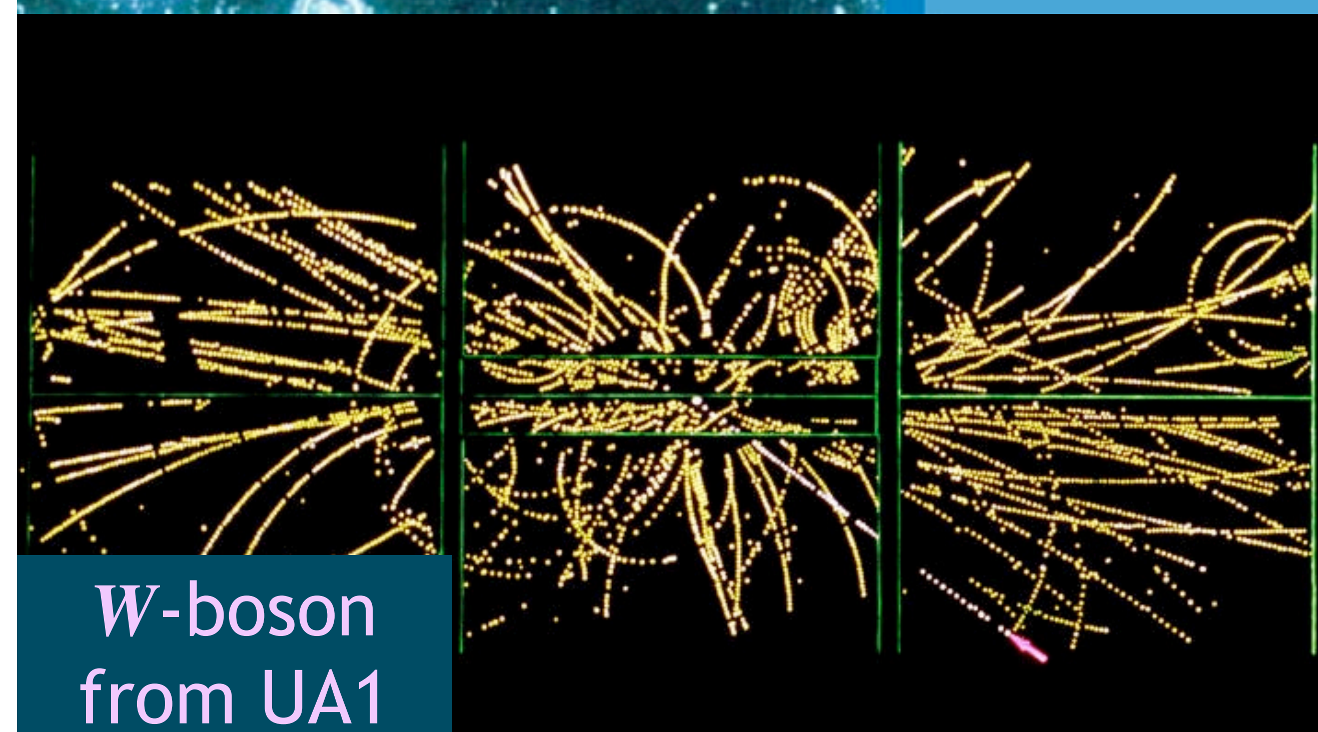
- *Z*-boson interactions were first observed 1973 at CERN Gargamelle experiment through
$\overline{\nu}_\mu\, e^- \rightarrow \overline{\nu}_\mu\, e^-$



- Real (as opposed to virtual) *W* and *Z* bosons were first observed 1983 at UA1 and UA2 experiments at CERN in $p\overline{p} \rightarrow WX$, $p\overline{p} \rightarrow ZX$
(Noble prize 1984)

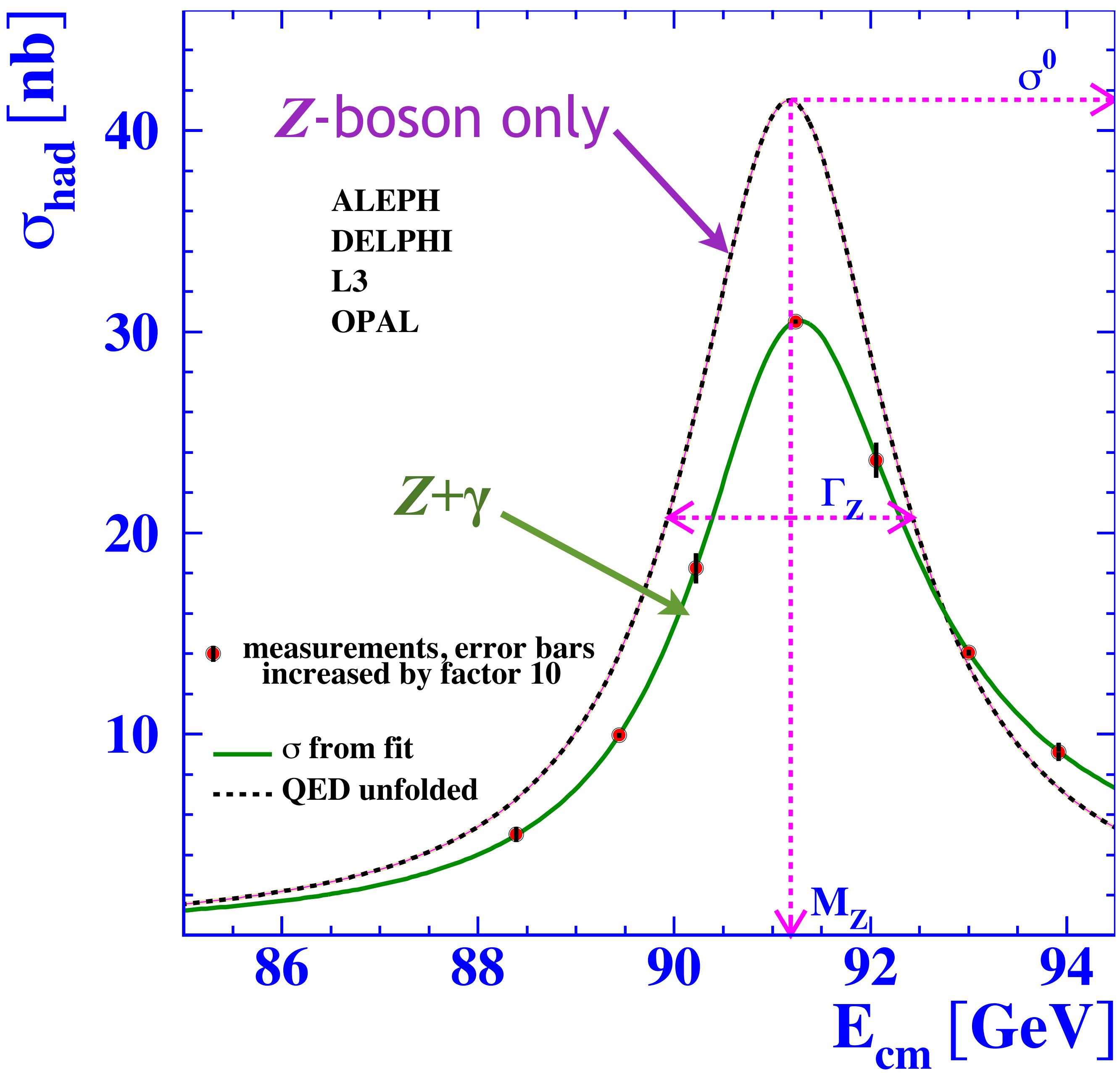


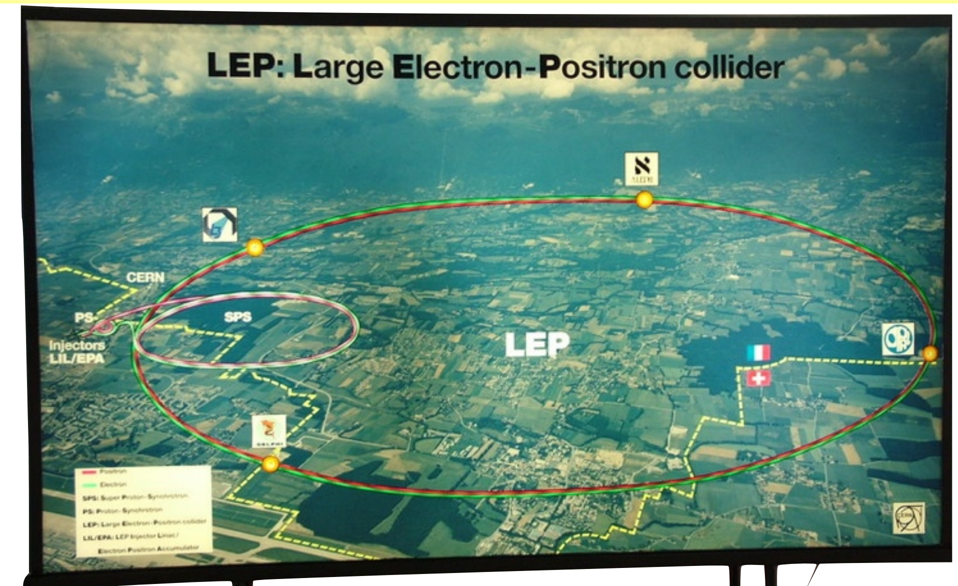
Z-boson event from Gargamelle



W-boson from UA1

W and *Z*-boson measurements





- Z^0 bosons studied at Large Electron Positron (LEP) Collider at CERN.
- Approximately ~1M events at $\sqrt{s} \sim m_Z$: $e^+e^- \to Z^0 \to f\overline{f}$
- Measured mass and total width:
  - $m_Z = 91.1876 \pm 0.0021$ GeV
  - $\Gamma_Z = 2.4952(23)$ GeV
- *W* bosons studied at LEP and Tevatron collider at Fermilab
- Measured mass and total width:
  - $m_W = 80.385 \pm 0.015$ GeV
  - $\Gamma_W = 2.085 \pm 0.042$ GeV

Higgs Coupling to Bosons

- Non-rigorous arguments for the ***W*** and ***Z*** boson masses.
- Consider the interactions between the minimum of Higgs field and ***W*** and ***B*** bosons:

$$\left(g_W W^a \tau^a + g'_W B^0\right)\begin{pmatrix}0\\v\end{pmatrix} = \left(g_W \begin{pmatrix}W^3 & W^1 - iW^2\\ W^1 + iW^2 & -W^3\end{pmatrix} + g'_W B^0\right)\begin{pmatrix}0\\v\end{pmatrix}$$

$$= v g_W (W^1 - iW^2) + v(-g_W W^3 + g'_W B^0)$$

$$= \sqrt{2} v g_W \left(\frac{W^1 - iW^2}{\sqrt{2}}\right) - v\sqrt{g_W^2 + g_W'^2}\,(W^3 \cos\theta_W - B^0 \sin\theta_W)$$

$$= \underbrace{\sqrt{2} v g_W}_{=2\sqrt{2}\,m_W}\, W^+ - \underbrace{v\sqrt{g_W^2 + g_W'^2}}_{=2m_Z}\, Z^0$$

τ^a: three Pauli matrices

Extra factor of √2 for ***W***-bosons as there's two of them: ***W***$^+$, ***W***$^-$

$$m_W = \frac{v\, g_W}{2} \qquad m_Z = \frac{1}{2} v \sqrt{g_W^2 + g_W'^2}$$

- Measured masses are $m_W = 80.385 \pm 0.015$ **GeV** and $m_Z = 91.1876 \pm 0.0021$ **GeV**.
- Implies: $$\cos\theta_W = \frac{g_W}{\sqrt{g_W^2 + g_W'^2}} = \frac{m_W}{m_Z}$$

$\alpha \sim 1/128$ at $E \sim m_Z$

- Using $e = g'_W \cos\theta_W = g_W \sin\theta_W = \sqrt{4\pi\alpha} \sim \sqrt{\frac{4\pi}{128}}$ gives **v=246 GeV**